Assessment of local and regional strategies to control bacteria levels at beaches with consideration of impacts from climate change

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ABSTRACT

The objective of this study was to evaluate relationships between local factors (beach geomorphology and management) and regional factors (infrastructure improvements and temperature changes) against levels of fecal indicator bacteria (FIB) at recreational beaches. Data were evaluated for 17 beaches located in Monroe County, Florida (Florida Keys), USA, including an assessment of sanitary infrastructure improvements using equivalent dwelling unit (EDU) connections. Results show that elevated FIB levels were associated with beach geomorphologies characterized by impeded flow and by beaches with lax management policies. The decrease in EDUs not connected coincided with a decrease in the fraction of days when bacteria levels were out of compliance. Multivariate factor analysis also identified beach management practices (presence of homeless and concession stands) as being associated with elevated FIB. Overall, results suggest that communities can utilize beach management strategies and infrastructure improvements to overcome the negative water quality impacts anticipated with climate change.

1. Introduction

Contamination of recreational waters can expose the public to a wide range of disease-causing microorganisms (Torres-Bejarano et al., 2016). Furthermore, studies have shown that fecal contamination increases perceived health risks among beachgoers (Praveena et al., 2013, 2015; Byappanahalli et al., 2008). In a prospective cohort study among beachgoers, swimmers in beaches near contaminated sources were more likely to develop waterborne illness (Arnold et al., 2013; Dorevitch et al., 2015). Quite alarmingly, children account for the largest burden waterborne illness (Arnold et al., 2016; Ford and Colwell, 1995, Young, 2016; Wade et al., 2008). The most recent statistics on U.S. waterborne diseases were reported in a June 2015 Morbidity and Mortality Weekly Report (MMWR) (MMWR, 2015), which states that during 20,011–2012, public health officials from 32 states and Puerto Rico reported 90 recreational water–associated disease outbreaks. Twenty-one (23%) were associated with untreated recreational water. These outbreaks resulted in 479 cases (27% of all outbreak-related cases) and 22 (24%) hospitalizations. Gastrointestinal

Illness (GI) associated with symptoms such as diarrhea, nausea, vomiting, fever, and abdominal pain was responsible for the majority of the cases.

Many of the infectious agents of concern in recreational water are the result of fecal pollution (Sousa et al., 2016). Sources of fecal pollution include human sewage (Elmir et al., 2007, 2009), surface runoff after rainstorms (Ahn et al., 2005, Molina et al., 2014), domestic animals (Wright et al., 2009; Dickerson et al., 2007), and wildlife (Converse et al., 2012; Sinigalliano et al., 2013). These sources can be enhanced further by a changing global climate, which include a rise of sea levels, increased precipitation (Vermeulen and Hofstra, 2014, Coffey et al., 2013), impacts from higher-frequency storms events, and higher air/water temperatures. Recreational waters located in areas where climate change causes increased precipitation and runoff are more likely to become contaminated with pathogens (Dorfman and Haren, 2013).

To evaluate potential health effects of infectious agents in recreational waters, health departments typically measure the level of fecal indicator bacteria (FIB). FIB are microbial indicators used to evaluate

beach water quality due to potential sewage sources (Shibata et al., 2004). High FIB presents greater health risks. For marine recreational beaches in Florida, enterococci (U.S. EPA, 2012) and fecal coliform (FDEP, 2016) have been routinely monitored.

FIB at beaches are influenced by local beach specific factors. These factors include beach geomorphology, which controls water circulation along with the specific ways in which beaches are managed (Whitman and Nevers, 2004). FIBs are also influenced by regional factors, including larger scale infrastructure improvements for sewage disposal and changes in environmental factors, such as temperature.

With respect to local beach specific factors, beach geomorphology was found to serve as a predominant factor associated with excessive FIB levels. Donahue et al. (2017) categorized the 316 beaches in Florida into one of six categories, finding that open coast beaches, defined as those located on barrier islands directly facing either the Atlantic Ocean or Gulf of Mexico, had the best water quality as a group. Beaches located within bays behind the barrier islands, had the second-best water quality and were followed by beaches that were located within marsh areas. The differences in FIB exceedances at each of these beaches were attributed in part to wave action and bottom slope near the shore (Feng et al., 2016). Kelly et al. (2018) in a follow-up study, demonstrated that beach management approaches influence FIB exceedances at beaches. For the 211 open-coast beaches evaluated by Kelly et al., lower FIB exceedances were associated with low densities of seaweed and animals (humans, dogs, and birds), policies for managing birds, procedures for charging access fees, and methods of controlling storm water.

With respect to regional factors, the motivation for monitoring FIB was to protect against point sources of pollution, from leaking sanitary sewage infrastructure. Lack of proactive urban planning and the lack of quality infrastructure contribute to potential contamination on beaches (de Sousa et al., 2013). Water contamination by human waste (Whitman et al., 2007) is tied to failure of local urban or rural water infrastructure, including municipal wastewater, septic, and storm water systems (Balbus et al., 2016; Crowther et al., 2001; Iverson et al., 2017). Over time, the sewer infrastructure in Monroe County has varied from very poor sewage treatment systems such as latrines and cesspits during the last decade, to more sophisticated on-site sewage disposal systems such as septic tanks. Entering into the new millennia Monroe County has implemented additional collection and treatment of sewage at centralized wastewater treatment plants (Paul et al., 1995; Paul, 2000). The method of sewage collection can be via gravity, which is subject to leakage and infiltration, to "tighter" vacuum sewage collection systems, which tend to be air tight (Wolf et al., 2004, Vollertsen and Hvitved-Jacobsen, 2003). The degree of treatment at wastewater treatment plants can also vary from simple primary treatment, which focuses on the removal of settleable solids, to secondary treatment, which removes dissolved organic waste. Advanced wastewater treatment processes purify the water even further. The disposal of the effluent can be via ocean outfall, which has a direct influence on coastal water quality (Watkinson et al., 2007) or via deep well injection, which may or may not indirectly influence coastal water bodies (Griggs et al., 2003). Thus, large scale infrastructure improvements designed to address sanitary sewage can potentially have a significant impact on FIB levels in coastal waters depending upon the way sewage is to be transported, treated, and ultimately disposed. Case studies have shown a decrease in fecal coliform bacteria in recreational waters subsequent to improved wastewater treatment facilities (Bhat and Danek, 2012).

Climate change has the potential to create a serious public health threat, affecting human health outcomes and disease patterns (Haines et al., 2006). One distinctive influencing factor is the anticipated change in temperature. The International Panel on Climate Change (IPCC, 2013) predicts increases in mean global temperature to vary between 1.0 and 3.7 °C by the end of the century. Microbial survival is related to temperature. Generally, optimal temperatures for microbial growth are in the 16 °C to 52 °C range with a doubling of rates of metabolism with every 10 °C increase in temperature (Salvato, 1992).

Currently, the mean average temperature in Key West, located at the southern end of Monroe County, is 25.5 °C (1948 to 2015 period of record, Key West International Airport, National Climatic Data Center). Using the IPCC estimates as a guide, climate change could result in a mean temperature increase of 26.5 °C to 29.2 °C. Of interest would be to observe how FIBs respond to such changes in temperature.

Recently, attention has focused on how coastal infrastructure will adapt to cope with anticipated climate effects (Bloetscher et al., 2010, Bloetscher, 2012, Flood and Cahoon, 2011, Dvorak et al., 2018). The objectives of this paper were to evaluate the influence of local beach-scale factors of geomorphology and beach management and to evaluate regional-scale factors, such as changes in sanitary infrastructure and the effects of temperature on FIB levels at beaches in Monroe County, Florida.

2. Methods

Fecal indicator bacteria levels (enterococci and fecal coliform) corresponded to the 17 recreational beach sites in Monroe County that are included within the Florida Healthy Beaches Program (FHBP) database (FDOH, 2018). Beach geomorphology was evaluated with the aid of Google images (Donahue et al., 2017). Beach management was assessed through a beach management survey (Kelly et al., 2018). Regional infrastructure was evaluated by gathering publically available information concerning sanitary projects and the progress of sewer connections (Monroe County Government, 2007, 2008, 2009, 2011, 2012, 2013, 2014, 2015). Additional information was gathered from three regional open forum meetings with local environmental government groups. Additional methodological details are provided below.

2.1. Fecal indicator bacteria and temperature data

FHBP has collected bacteria (enterococci and fecal coliform) and environmental data for coastal beaches throughout Florida, including Monroe County. For the current study, FIB and temperature data were retrieved from the FHBP database for the 2000 to 2015 period of record. Each FIB data point in the database was paired with a temperature value.

Through 2015, the Florida Department of Health (FDOH) followed the U.S. Environmental Protection Agency (EPA) criteria for enterococci (US EPA, 1986, 2012; Boehm et al., 2009). As such, the FDOH issues beach closures when enterococci exceeds the single sample maximum of 104 colony forming units (CFU) per 100 mL or if the five-sample geometric mean exceeded 35 CFU/100 mL. For fecal coliform, the FDOH would issue advisories when 400 CFU/100 mL fecal coliform were exceeded for single-samples, and 200 CFU/100 mL for geometric means (FDEP, 2016). By far the majority of the non-compliance was due to exceedance of single samples. Since beach closures are dictated by FIB values above threshold levels, all FIB data were converted to percent exceedance for the period of record available. Percent exceedances are defined as the percent of the samples that exceed the single sample maximum. For example, a 5% exceedance for enterococci implies that among 100 samples, 5 of them exceeded 104 CFU/100 mL. Data were available starting in August 2000 with biweekly samples collected through July 2002 for 16 of the 17 beaches (with the exception of Founders Beach). After 2002, all 17 beaches (including Founders) were sampled weekly through 2011. During 2011, the fecal coliform analyses were dropped, sampling was scaled back to bi-weekly, and 6 beaches were eliminated from the program (Islamorada Library, Anne's, Curry Hammock State Park, Coco Plum, Veteran's, and Simonton Street).

Correlation among FIB data were assessed statistically using Pearson correlation analysis based upon the methods of least squares. Values of $R^2 > 0.3$ and p values < 0.05 were considered significant.

Table 1

Beaches in Monroe County ordered geographically from north (top row) to south (bottom row). Data include beach geomorphological categories (back reef, bay, and structure protected) and FIB measures (geometric mean, percent exceedance, and number of data points) for enterococci and fecal coliform.

Beach name	Beach category	Enterococci			Fecal coliform		
		Geo. mean	Percent exceed	# Data points	Geo. mean	Percent exceed	# Data points
John Pennekamp State Park	Bay	6.3	4.2	618	6.4	2.4	498
Harry Harris County Park	Struct. protect.	5.1	3.2	618	5.9	3.0	498
Founders	Bay	4.9	3.0	563	3.7	0.9	445
Islamorada Library	Bay	7.9	3.4	506	8.2	0.6	498
Anne's	Back reef	4.8	2.8	506	4.4	1.0	497
Curry Hammock State Park	Bay	5.1	2.6	500	4.6	0.2	491
Coco Plum	Back reef	6.7	7.5	506	5.0	2.0	498
Sombrero	Back reef	5.6	2.9	616	4.3	0.6	496
Veteran's	Back reef	4.1	2.2	506	3.8	0.0	498
Bahia Honda Sandspur	Back reef	5.3	3.2	617	3.1	0.6	498
Bahia Honda Oceanside	Back reef	5.5	4.1	616	3.9	0.6	498
Bahia Honda Bayside	Bay	3.9	1.0	615	3.4	0.4	498
Smather's	Back reef	5.6	4.7	617	7.6	2.8	498
Higgs	Struct. protect.	13.5	12.9	619	17.4	9.2	498
South	Struct. protect.	13.4	11.9	586	14.4	10.8	465
Simonton Street	Struct. protect.	6.0	3.0	462	11.0	3.1	454
Ft. Zachary Taylor State Park	Back reef	3.1	0.6	617	4.0	1.0	497

2.2. Beach geomorphology and management practices

The physical geography of the Keys, along with that of human-made structures, are contributing factors that characterize its geomorphology and, as a result, influence nearshore flow of water. Efforts to evaluate both natural and manmade geographical features and beach management procedures consisted of evaluating the sites through Google Earth imagery and through beach surveys. Google Earth analysis followed the methods of (Donahue et al., 2017) and resulted in the categorization of the 17 Monroe County beaches into one of three categories: Back Reef, Bay, and Structure Protected (Table 1). Back reef beaches correspond to the majority of the beaches in Monroe County (n = 8). The beaches in Monroe County are an extension of the barrier island formations along the eastern Florida coastline. They are situated behind shallow coral reefs that dissipate wave energy onto the beaches. Bay beaches (n = 5) are on the bay side of the Monroe County archipelago and typically have little to no wave action. At some beaches, significant structures have been built around them limiting water circulation (n = 4). In this study, these beaches have been classified as manmade-structure-protected beaches. The degree to which water is obstructed is variable. To categorize beaches within the manmade-structure-protected category, the obstruction must block longshore flow (the obstruction is many times perpendicular to the coastline) and must be longer than the beach itself. Piers that are supported on columns allowing water to flow below are not considered an obstruction. Piers with solid walls extending to the bottom sediment (pier walls) are considered an obstruction.

The beach management section of this study was conducted as described in Kelly et al. (2018), in which a beach management and policy survey was developed to evaluate all beaches in Florida that are part of the FHBP. The team received a 100% response rate for the 17 beaches in Monroe County. The results from the Monroe County survey were then analyzed against the percent exceedance for enterococci and fecal coliform. Since beach management policies are in place for long periods of time, on the order of many years, this study used the entire period of record, 15 years, to define a beach's overall average exceedance rate (percentage of time the beach FIB exceeds the regulatory thresholds).

The data were analyzed statistically using SAS (SAS 9.4, SAS Institute, Cary, North Carolina) and Microsoft Excel. The open-ended questions were coded into categories and analyzed through ANOVA. F-values significantly > 1 and p-values < 0.05 were considered significant. t-tests were performed, using the Satterthwaite method, as the equality of variances is unknown and assumed to be unequal for groups evaluated.

2.3. Regional infrastructure improvements

Historically, sewage disposal in Monroe County has relied on cesspits and septic tanks. The Monroe County Wastewater Plan developed in June of 2000 laid out goals with recommendations outlined to implement the plan. This plan included designating service areas or districts to manage wastewater efficiently. The goals included upgrades to all wastewater treatment plants (WWTP) such that they would implement Advanced Wastewater Treatment (AWT) or Best Available Technologies (BAT). The effluent standards for AWT include 5 mg/L (mg/L) for biological oxygen demand, 5 mg/L for total suspended solids, and 3 mg/L for total nitrogen and 1 mg/L for total phosphorus. For BAT they include 10 mg/L BOD, 10 mg/L TSS, 10 mg/L TN and 1 mg/l TP (FLA. STAT., 1999). In order to document wastewater treatment system improvements, annual wastewater implementation reports were compiled (Monroe County Government, 2007, 2008, 2009, 2011, 2012, 2013, 2014, 2015) (Fig. 1).

The 2000 Monroe County Wastewater Plan separated the Florida Keys into a sequence of wastewater project or service areas. As of 2015, there were 14 service areas corresponding to 8 separate management entities. The management entities consist of local municipalities or the Florida Keys Aqueduct Authority (FKAA), which manages 6 service areas. Given the longitudinal extent of Monroe County, the 14 service areas can be clustered into three geographic regions: the Upper, Middle, and Lower Keys (Fig. 2).

In the Upper Keys, there are three wastewater service areas: Ocean Reef (North Key Largo Utility Corporation), Key Largo (Key Largo Wastewater Treatment District), and Islamorada (Islamorada, Village of Islands). Of the five beaches located in the Upper Keys, two are within the Key Largo service area (John Pennekamp and Harry Harris), and three are within the Islamorada service area (Founders' Park, Islamorada Library, and Anne's).

There are five wastewater service areas in the middle Keys. They include Layton (City of Layton), West & East Long Key (FKAA), Duck and Conch Key Regional (FKAA), Marathon (City of Marathon), and Key Colony Beach (City of Key Colony Beach). There are three beaches located within the City of Marathon service area (Curry Hammock, Coco plum, and Sombrero).

The southernmost six service areas of the lower Keys include Cudjoe (FKAA), Bay Point (FKAA), Big Coppitt (FKAA), Stock Island (Key West Resort Utilities Corporation), Key West (City of Key West), and Key West Naval Air Station. Four beaches are located within the northern extreme of the Cudjoe service area (Veteran's, Bahia Honda Bayside,
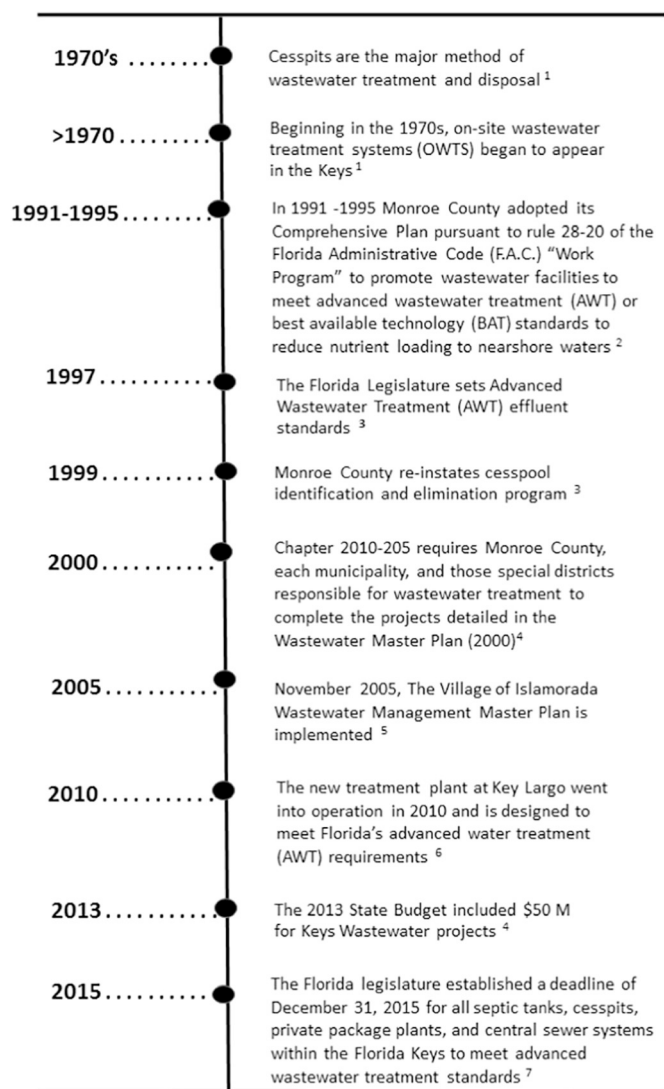
Fig. 1. Timeline of major policies and reports that impact Florida Keys wastewater transmission and treatment. (References: [1]Darden, 2001, [2]Florida Dept. of Environmental Protection (FDEP), 2008, [3]U.S. Army Corps of Engineers and South Florida Water Management District (SFWMD), 2004, [4]Wood, 2012, [5]Martin, 2012, [6]Key Largo Wastewater Treatment District, 2017, [7]Florida Statutes, 2017a, b)

Bahia Honda Oceanside, and Bahia Honda Sandspur) and 5 are located in the city of Key West (Smathers, Higgs, South, Ft. Zachary Taylor, and Simonton). To obtain a balance for the number of beaches among the different regions, the four beaches in the Cudjoe service area were considered part of the Middle Keys.

As part of measuring progress towards comprehensive wastewater treatment within the Florida Keys, the number of wastewater connections, reported in units of equivalent dwelling units (EDU), are reported for each of the service areas. An EDU is defined as a measure where one unit is equivalent to wastewater effluent from one home. The county's 2000 Wastewater Master Plan defines an EDU equal to 631 L per day per home. This value is for the purpose of assessing rates and fees (Sleasman, 2011). The EDUs per service area were compiled for the period from 2000 to 2015.

To further our understanding of the changes in infrastructure improvements, a series of three open-forum town hall meetings were organized to present, confirm, and expand the information that was gained through literature reviews. We felt it vital to gather different levels of government and stakeholder groups, as research indicates that

when a common-pool resource is threatened, various agencies and stakeholder groups are more likely to collaborate (Sleasman, 2009). The meetings were held between August and September 2014 with representatives from municipal, county, state, and federal agencies plus representatives from local wastewater service areas. Three meetings were scheduled and geographically distributed within the Upper, Middle, and Lower Keys to allow reasonable access to those interested in attending. The meetings had three aims: to review and discuss the results from beach management surveys; to show water quality data compiled from the FHBP database; and third, to open the floor to discussion of the wastewater infrastructure improvements and how they may correlate with improvements in beach bacterial levels. These meetings brought together various entities and opened up dialog between groups that seldom have the opportunities to meet because of various logistical reasons. The minutes from the meetings are included in the supplemental text.

2.4. Factor analysis

All of the responses from the beach management survey were analyzed together with the data gathered for EDUs, water temperatures, and air temperatures through SAS factor analysis to evaluate which measures had the greatest correlation with enterococci exceedances. Since it is likely that some of the beach management practices were auto correlated, these measures could not be assumed independent. Therefore, factor analysis was conducted to collapse these beach measures in an effort to address possible autocorrelation. Since beach management practices were assumed constant throughout the period of record, three years were chosen for analysis (2007, 2011, and 2015). These years corresponded to the beginning, middle, and end of the period of study. In this way the data for EDUs and average yearly temperatures could be integrated with beach management practices within the multivariate analysis. From the multivariate analysis, measures and consolidated factors were identified which accounted for most of the variance of enterococci exceedances. Using linear regression, the effects of these measures and factors was examined on enterococci exceedances. The coefficient of multiple determination (R^2) was evaluated to determine the proportion of variance for the exceedances that was explained by the model. The *p*-values were also used to determine which of the factors were the most significant.

3. Results

3.1. Fecal indicator bacteria

FIB results were evaluated for the period of record for both geometric mean levels and percent exceedance. FIBs were also evaluated on an annual basis. When evaluating the geometric means over the period of record, South Beach and Higgs Beach showed the highest levels of FIBs (Table 1). Although these beaches were the highest, they did not exceed, on average, the 35 CFU/100 mL threshold for enterococci or the 200 CFU/100 mL threshold for fecal coliform (Table 1).

Evaluation of the percent exceedance, showed that beaches were out of compliance on occasion, even though the geometric means were low (Table 1). South Beach and Higgs Beach showed enterococci exceedance levels > 10% of the times, while three of the seventeen beaches, Veteran's Beach, Bahia Honda Bayside and Ft. Zachary Taylor, showed low exceedance values below 2.5%. When evaluating fecal coliform, South Beach and Higgs Beach also had the highest percent exceedances (> 9%). The lowest percent exceedances for fecal coliform were observed in the central part of the county from Curry Hammock State Park through Bahia Honda Sandspur, with the exception of Coco Plum Beach. Generally, percent fecal coliform exceedance was correlated with the enterococci exceedance ($R^2 = 0.82$, $p < 0.01$).

When evaluating the FIB data in time series on an annual basis, the overall trend was that of a general decrease in FIB with time (Fig. 3).
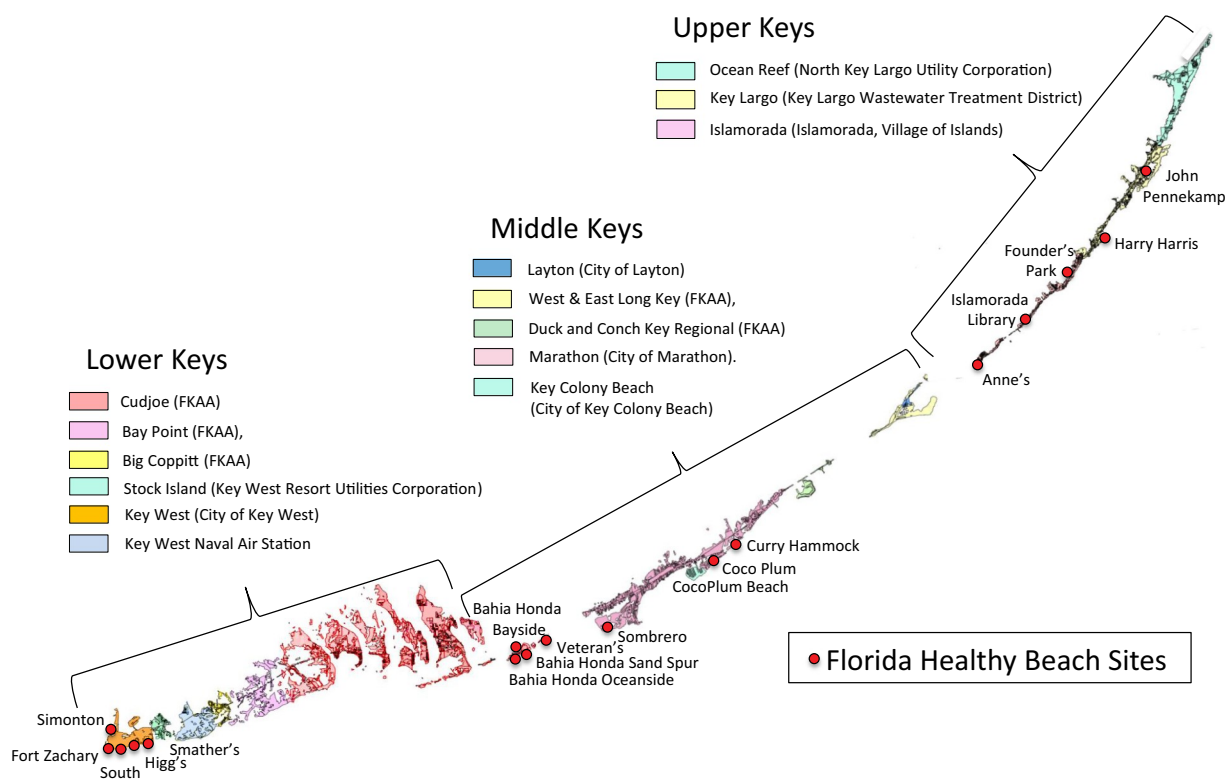
Upper Keys

■ Ocean Reef (North Key Largo Utility Corporation)
■ Key Largo (Key Largo Wastewater Treatment District)
■ Islamorada (Islamorada, Village of Islands)

Middle Keys

■ Layton (City of Layton)
■ West & East Long Key (FKAA),
■ Duck and Conch Key Regional (FKAA)
■ Marathon (City of Marathon).
■ Key Colony Beach
   (City of Key Colony Beach)

Lower Keys

■ Cudjoe (FKAA)
■ Bay Point (FKAA),
■ Big Coppitt (FKAA)
■ Stock Island (Key West Resort Utilities Corporation)
■ Key West (City of Key West)
■ Key West Naval Air Station

John Pennekamp
Harry Harris
Founder's Park
Islamorada Library
Anne's

Curry Hammock
Coco Plum
CocoPlum Beach

Bahia Honda Bayside
Veteran's
Sombrero
Bahia Honda Sand Spur
Bahia Honda Oceanside

Simonton
Fort Zachary
South
Higg's
Smather's

● Florida Healthy Beach Sites

Fig. 2. Beaches and wastewater treatment service areas in Monroe County separated by the upper, middle, and lower Keys regions.

Exceptions include John Pennekamp, which showed a short-term spike during 2012 and 2013. As observed from the change in the vertical y-axis on these plots, the range in FIB levels increases as one proceeds southward from the Upper Keys to the Lower Keys, with Higgs and South Beach showing the largest range, with accompanying decreases in FIB levels over time.

3.2. Beach geomorphology and management

3.2.1. Beach geomorphology

In Monroe County, the 17 beaches can be categorized into five Bay beaches (Bahia Honda Bayside, Curry Hammock, Founders' Park, Islamorada Public Library Beach, and John Pennekamp State Park), four Manmade Structure Protected beaches (Harry Harris State Park, Higgs Beach, Simonton Beach, and South Beach), and eight Back-Reef beaches (Anne's Beach, Bahia Honda Oceanside, Bahia Honda Sandspur, Coco Plum Beach, Fort Zachary Taylor State Park, Smathers Beach, Sombrero Beach, and Veterans Beach). Google Earth images for each of these beaches are available in the supplemental text. Among these beach categories, the Manmade Structure Protected beaches had higher mean fecal coliform percent exceedances (7.8% for enterococci and 6.5% for fecal coliform) relative to Bay beaches and Back-Reef beaches (mean percent exceedance values ranging from 0.9 to 3.5%). The differences in the means were statistically significant for fecal coliform (p = 0.001) but not statistically significant for enterococci (p = 0.508) (Table 2).

3.2.2. Beach management

Beach-specific FIB values and survey data were analyzed in six categories: human use, animal densities and control, solid waste management, aspects that would alter the sediment distribution at the beach, general policies concerning beach access and how the beach can be used, and impacts from sources outside the beach environment through drainage and the sanitary infrastructure.

3.2.2.1. Human use. Human use was examined through questions about the densities of visitors (Table 4) and presence of homeless populations (Table 3). To evaluate human densities, we asked beach managers for the densities for average Sundays and average Wednesdays at noon for comparison purposes. Possible answers of "zero", "sparse", "medium", and "dense" were requested and the choices were accompanied with pictures to illustrate the definition of these terms. The vast majority of the beach managers' reported "medium" densities of humans at the beach. No statistical differences in FIB exceedances were noted for beaches with different densities of humans. Managers for the four beaches reported homeless populations on beaches. Beaches with homeless populations had higher exceedances of enterococci by a factor of 2.6 and for fecal coliform by a factor of 6.3 relative to beaches without reported homeless populations. The differences, however, were statistically not different, although the differences in fecal coliform exceedances among beaches with and without homeless populations were close to significance (p = 0.08).

3.2.2.2. Animal densities and control. Animal densities were evaluated in separate categories determined by the type of animal (dogs and birds, and wildlife other than birds). For the animal categories, the densities were evaluated in much the same way as human use. Dog densities were evaluated for the density of dogs at the beach on Sundays and Wednesdays at noon (Table 4). The "dense" category had the highest enterococci exceedances on both Sunday and Wednesday; however, these exceedances were not statistically different. Similarly, enterococci and fecal coliform exceedances were higher for beaches that allow dogs or that allow dogs to visit (Table 3), in comparison to beaches that do now allow dogs or do not have canine visitors. As before, however, the exceedances were not statistically different.

The vast majority of beach managers (16 of 17) report the presence of birds at beaches. The types of birds reported include seagulls, parrots, and mockingbirds. The majority report medium to sparse densities of birds. No distinct trends were observed between the different reported densities of birds. Two of the 16 reporting beaches have policies
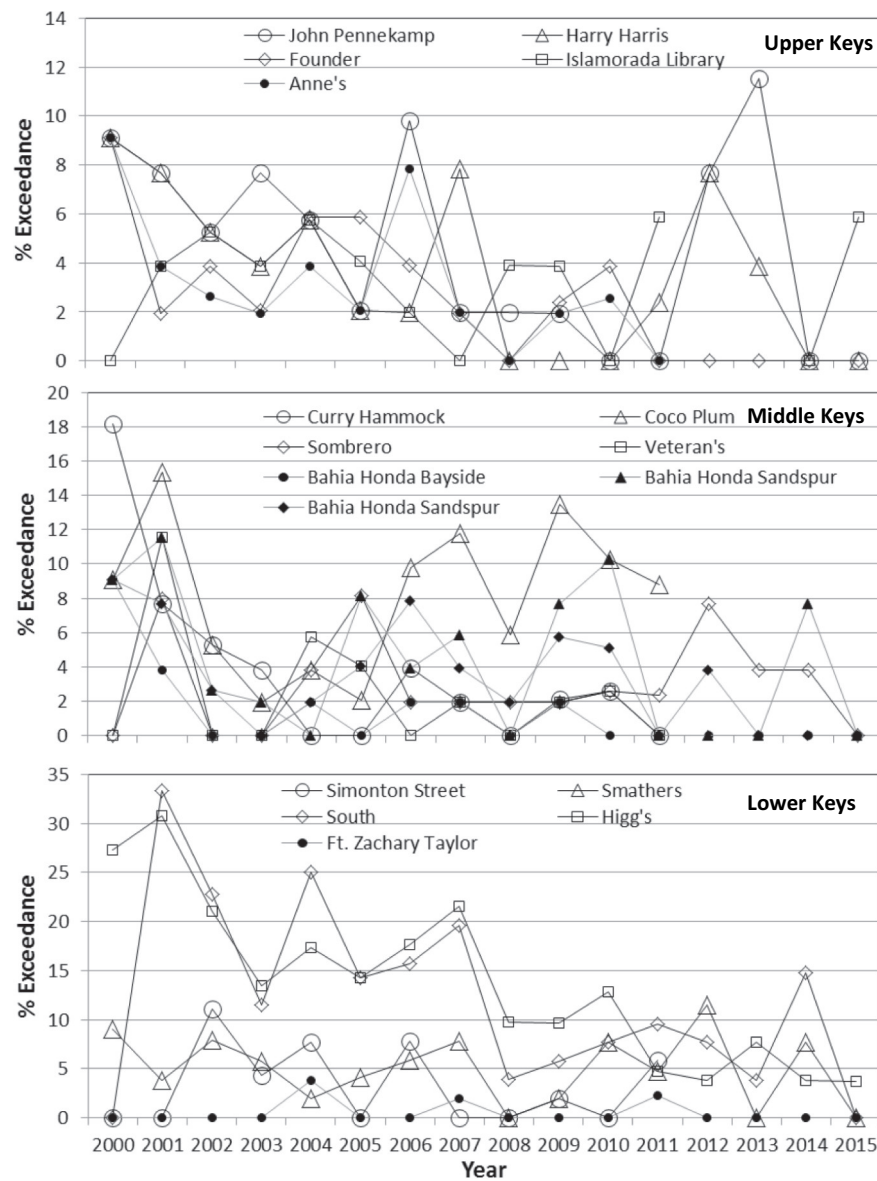
Fig. 3. Time series plots of enterococci percent exceedance for beaches located in the upper, middle, and lower Keys (from top to bottom panel).

for managing birds at the beach. Although the average FIB for the two beaches with bird policies were lower than the 16 beaches that did not have policies for managing birds, the levels were not statistically different. Additional wildlife reported at Monroe County Beaches included iguanas (n = 8), raccoons (n = 5), and feral cats (n = 3). No statistical differences in FIB were observed for beaches with specific reports of other wildlife.

3.2.2.3. Solid waste management. Of the respondents who answered the question about the frequency of garbage collection (n = 11), the majority had garbage collection on the order of days with only one reporting garbage collection on a weekly basis. Also, the vast majority of beaches report covered trash cans (n = 12) whereas only a minority (n = 3) reported no covers. Although the beaches with covered trash cans had slightly lower FIB exceedances relative to those without trash covers, the differences were not statistically significant.

Table 2
Enterococci and fecal coliform percent exceedance statistics by beach type.

Beach type	Enterococci				Fecal coliform			
	Mean % exceed.	Std. dev	Range	Statistical significance[a]	Mean % exceed.	Std. dev	Range	Statistical significance[a]
Type 2, bay (n = 5)	2.83	1.19	0.98–4.21 (3.23)	A	0.90	0.88	0.20–2.41 (2.21)	B
Type 6, back-reef (n = 8)	3.50	2.02	0.65–7.51 (6.86)	A	1.08	0.90	0.00–2.81 (2.81)	B
Type 4, manmade-structure-protected (n = 4)	7.78	5.39	3.03–12.9 (9.89)	A	6.52	4.06	3.01–10.75 (7.74)	C

[a] Beach types sharing the same letter are statistically not different.

Table 3

Statistics of enterococci and fecal coliform percent exceedances when compared to beach management survey responses for questions with "yes" or "no" answers.

Question	Yes	n	No	n	p value
Homeless present					
Enterococci	8.15	4	3.13	13	0.138
Fecal coliform	6.47		1.03		0.076
Dogs allowed					
Enterococci	6.60	4	3.61	13	0.302
Fecal coliform	3.73		1.87		0.416
Dogs visit anyways					
Enterococci	3.87	8	3.20	5	0.620
Fecal coliform	2.17		1.38		0.581
Bird policies					
Enterococci	3.40	2	4.70	14	0.345
Fecal coliform	1.31		2.54		0.455
Garbage cans covered					
Enterococci	3.71	12	3.73	3	0.991
Fecal coliform	1.76		2.03		0.800
Regular beach grooming					
Enterococci	6.05	8	2.77	9	0.069
Fecal coliform	3.67		1.10		0.122
Sand renourished					
Enterococci	5.25	10	2.97	7	0.182
Fecal coliform	3.36		0.80		0.091
Maintenance vehicles on beach					
Enterococci	4.70	13	3.04	4	0.147
Fecal coliform	3.04		1.40		0.302
Charge fees					
Enterococci	2.75	8	5.70	9	0.070
Fecal coliform	1.14		3.35		0.138
Have concession stands					
Enterococci	9.69	3	3.16	14	0.138
Fecal coliform	7.47		1.20		0.133
Marinas Near Beach					
Enterococci	3.06	7	5.19	10	0.16
Fecal coliform	1.29		3.02		0.20
Storm water management					
Enterococci	4.18	11	6.42	3	0.513
Fecal coliform	2.15		3.99		0.644
Public restrooms					
Enterococci	4.39	16	3.03	1	N/A
Fecal coliform	2.26		3.08		N/A

3.2.2.4. Aspects that alter the sediment distribution at the beach. This section addresses seaweed, beach grooming, and renourishment. The first series of questions focused on seaweed. Most of the reporting beaches (n = 7) indicate "medium" densities of seaweed. No trend was observed between reported seaweed density and FIB levels (Table 4). Beaches that were groomed report higher FIB exceedances relative to those that were not groomed. Similarly, beaches that have been renourished have higher FIB exceedances relative to those that have not been renourished. In either case, the differences were not statistically significant.

3.2.2.5. General policies concerning use. This section considers beach access, and the ways in which the beaches are used. Policies concerning beach use included 1) lifeguards, 2) vehicles on the beach, public and maintenance, 3) fees to access the beach, 4) concession stands and 5) marinas near the beach. These factors are related to economics: if an agency that manages the beach charges fees for access, that agency then has funding to pay for lifeguards and maintenance vehicles. Funding can also be provided through amenities such as concession stands and marinas.

No beaches were reported to have lifeguards, so comparative statistics could not be performed. For vehicles, none allow cars from the general public on the beach but a vast majority (13 of 17) allows maintenance vehicles. Beaches that allowed maintenance vehicles were characterized by higher FIB relative to those that did not. Beaches that did not charge access fees were characterized by higher FIB relative to

those that did. Beaches with concession stands had higher FIB. Contrary to what would be expected, beaches with marinas nearby had lower FIB levels. However, none of the differences with respect to vehicular traffic, concessions, and marinas, were statistically significant.

3.2.2.6. Drainage and sanitary infrastructure. This section considers the associations between storm drainage and sanitary infrastructure and FIB levels. Our first question asked how storm water is managed at the beaches. We divided the answers into two categories, one where there was an attempt to manage storm water by transporting it away from the beach, retaining it, use of subsurface disposal, or avoiding paved areas at the beach, and another where there is no attempt to manage storm water. The beaches that had a system of storm water management in place were characterized by lower FIB levels relative to those that did not have a system in place.

Only 1 beach reported to not have a public restroom available. The percent exceedance for this beach was close (3.0% for enterococci and 3.1% for fecal coliform) to the mean percent exceedance for the beaches that have public restrooms available (4.4% for enterococci and 2.3% for fecal coliform). Differences were not statistically significant.

Overall, in Monroe County, the trends observed in FIB exceedance levels are consistent with what is known about FIB sources. We observed from the data that higher percent exceedances were associated with beaches whose water circulation is restricted (Manmade Structure Protected), have homeless populations, allow dogs, have high density of dogs, do not have policies for handling birds, have uncovered trash cans, allow maintenance vehicles on the beach and have concession stands, do not charge fees to access the beach, and do not have a system in place for handling storm water. Although all of these trends are consistent with the management of FIB sources, none of the differences were statistically significant. This may be due to the small sample size of beaches (n = 17) available through this focused study on Monroe County. Also, some results were the opposite of what would have been expected based upon FIB management. These included higher FIB exceedances for beaches that are groomed, that have been renourished, and which are farther from marinas. Again, in this case, differences were not statistically significant.

3.3. Regional infrastructure improvements

Prior to the 1970's, the major method of wastewater disposal was through cesspits, which discharged minimally treated sewage to the environment. In the 1970's, onsite treatment systems started to emerge throughout the Keys; by 1999, advanced wastewater effluent standards were developed. A major organizational advancement was obtained through the Florida Keys Wastewater Masterplan of 2000. With the implementation of the Wastewater Master Plan, Key West converted from ocean outfall to deep well injection in 2006 and is currently continuing improvements to address storm water runoff. The Village of Islamorada implemented its master plan in 2005. It involved the installation of vacuum sewers with discharge and treatment in Key Largo. A new treatment plant implementing AWT processes went into operation in Key Largo in 2010. The FKAA acquired additional facilities in the Lower Keys, serving Stock Island and Big Coppitt, allowing for the implementation of upgrades. By the end of 2015, all centralized wastewater treatment systems in the Florida Keys were to meet AWT standards. As of the September 2015 Connection Report (Monroe County, 2015), four out of the 14 service areas have 100% EDU connections. West and East Long Key, Cudjoe, and Key West Naval Air Station have 0%.

Comparing percent exceedance for all Monroe County beaches collectively against sewage connections (Fig. 4) shows that as the EDUs not connected decreased over time, the percent exceedances decreased. Each of these parameters decreased significantly over time ($R^2 = 0.95$, $p < 0.01$ for EDUs not connected, $R^2 = 0.63$, $p < 0.01$ for percent exceedance). From 2000 to 2015, the percent EDUs not connected

Table 4
Statistics of enterococci and fecal coliform percent exceedances when compared to beach management survey responses for questions related to density of potential contaminant source.

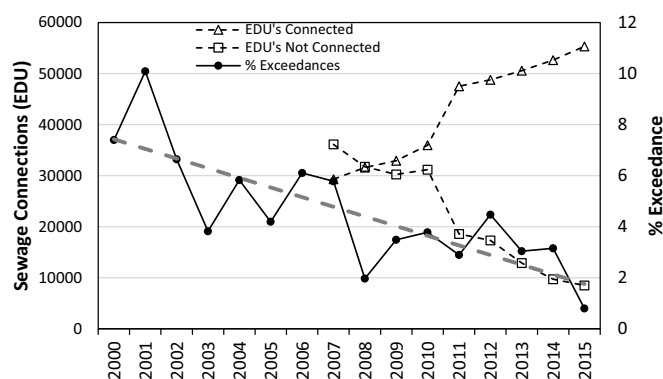| Question	Mean % exceed	n	Mean % exceed	n	Mean % exceed	n	Mean % exceed	n	Mean % exceed	n	p value
	Dense		Medium		Sparse		Zero		No Response		
Human density at noon Sunday											
Enterococci	3.05	3	4.85	12	3.03	1			2.92	1	0.828
Fecal coliform	0.84		2.75		3.08				0.60		0.764
Human density at noon Wednesday											
Enterococci			3.96	11	5.30	5	3.24	1			0.754
Fecal coliform			1.54		3.85		3.01				0.393
Dog density at noon Sunday											
Enterococci	7.51	1	2.92	1	5.49	8	2.71	7			0.337
Fecal coliform	2.01		0.60		3.55		1.18				0.501
Dog density at noon Wednesday											
Enterococci	7.51	1			6.28	6	2.81	10			0.081
Fecal coliform	2.01				4.41		1.07				0.103
Bird density at noon Sunday											
Enterococci	2.76	3	4.85	5	4.72	8	3.03	1			0.832
Fecal coliform	0.54		2.35		2.85		3.08				0.764
Bird density at noon Wednesday											
Enterococci	2.76	3	4.85	5	4.72	8	3.03	1			0.832
Fecal coliform	0.54		2.35		2.85		3.08				0.764
Maximum amount of seaweed											
Enterococci	3.85	6	5.44	7	3.04	4					0.520
Fecal coliform	1.10		3.86		1.40						0.227

Fig. 4. Sewage connections in equivalent dwelling units (EDU) versus percent exceedance for enterococci. Best fit line of percent exceedance for all Monroe County beaches collectively is shown as a gray dashed line.

decreased from 61% to 25%. Similarly, the % exceedances of enterococci decreased from 7.4% to 0.8%. A regression analysis directly comparing EDUs not connected through time versus percent exceedances, however, shows a low correlation ($R^2 = 0.24$) that is not statistically significant ($p = 0.18$). The lack of statistical significance when comparing EDUs not connected to percent exceedance is likely due to additional factors that influence FIB levels (e.g., environmental factors and the increase in degree of treatment and other initiatives). However, the fact that both decrease in time is important and helps to support the hypothesis that EDUs contribute towards lower exceedances at the beaches.

3.4. Temperature and FIB levels

Temperature data from the FHBP shows a correlation of increasing FIB levels with increasing air and water temperature between the temperature range of 15 to 28 °C (Fig. 5). This is true for both arithmetic means and geometric means of the FIB data. The variations are more pronounced for the arithmetic means as opposed to the geometric

means. A double peak is observed in the data set, with a small one occurring in the 20 to 21 °C range and another larger one occurring in the 28 to 29 °C range. Fitting the geometric mean FIB data to a 4th order polynomial (Fig. 5, right panel) suggests that the peak for enterococci corresponded to a temperature of 30 °C, whereas the peak for fecal coliform corresponded to a temperature of 29 °C.

3.5. Factor analysis

Factor analysis consistently identified EDU connections as the parameter accounting for the most variance (38 to 52% depending upon the year). The next parameter was air temperature (33% to 35%) and water temperature (18 to 30%), followed by beach type (13 to 19%). Storm water management explained 6% of the variance. The factor analysis of the 15 beach management measures with orthogonal rotation identified two dominant factors. For 2007 and 2011 data, in Factor 1, the presence of homeless, presence of concession stands, and the water temperature made up the highest proportion; in Factor 2, the air temperature and water temperature made up the highest proportion. For 2015, the characteristics of the dominant measurements changed with Factor 1. These dominant measurements were composed of EDUs, fees to access the beach, and water temperature. The dominant measures for Factor 2 were beach grooming and sand renourishment.

4. Discussion

The results from this study provide insights on four potential factors that may influence beach water quality. These factors include local factors, such as beach geomorphology and management practices, and also include regional factors, such as sanitary infrastructure improvements and temperature. Results suggest associations between these influences and fecal indicator bacteria levels (enterococci and fecal coliform) at recreational beach sites.

With respect to beach geomorphology, beaches that had the most limited water circulation (i.e., man-made structure protected beaches) had the highest levels of FIB relative to beaches in the other categories. Higher percent exceedances of FIB were observed within the man-made
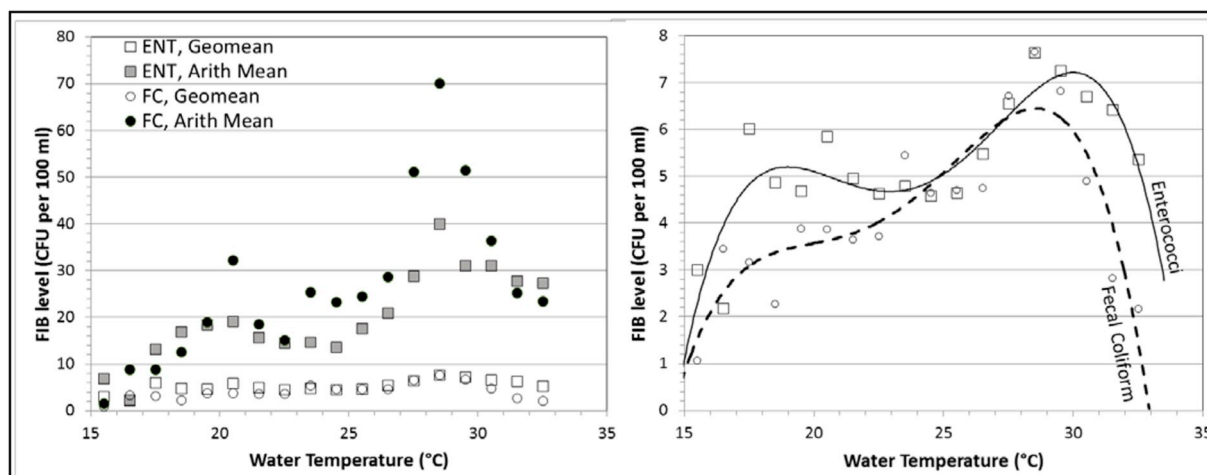
Fig. 5. Average FIB levels per degrees Celsius increase in water temperature. Left panel illustrates geometric and arithmetic means for enterococci (ENT) and fecal coliform (FC). The right panel emphasizes the variations observed in the geometric means. Lines correspond to 4th order polynomial fit of the data, with an $R^2 = 0.76$ for enterococci, and $R^2 = 0.81$ for fecal coliform.

structure protected beaches like those found at Higgs Beach and South Beach. Man-made structure protected beaches are characterized by impeded wave action and limited water circulation, which limits the dilution of bacterial sources. Higher exceedances with lower wave action are consistent with the observations by Feng et al. (2016). The effects from low wave action are compounded by limitations in water flow. Higgs Beach has a submarine wall that surrounds most of the beach and a pier wall on the open east side that greatly limits the flushing of water. South Beach is a narrow beach with two protruding pier walls that limit long-shore flushing. Several studies exist that show that areas of limited flushing are characterized by elevated FIB levels (Bordalo, 2003). For example, Lee et al. (2006) found elevated FIB levels at enclosed beaches in comparison to exposed beaches. The authors hypothesize that the quiescent environment at these beaches is the cause for the elevated FIB levels. Rippy et al. (2014) further attributes contaminated dry weather flows, even if small in amount, as the cause of elevated FIB at enclosed beaches. These results are consistent with the observation that manmade protected beaches and bay beaches are characterized by higher FIB levels.

When comparing the influence of beach geomorphology for the entire state of Florida, a more nuanced variation is observed. The State of Florida has a total of 5 Manmade Structure Protected beaches; four of these are found in Monroe County. Bay beaches throughout Florida (n = 71) were characterized by water quality (6.9% percent exceedance) similar to that of the state's Manmade Structure Protected beaches (6.5% percent exceedances). For Monroe County, the mean percent exceedance of the Manmade Structure Protected beaches (7.8%) was almost three times higher than for Bay beaches (2.8%). The difference in water quality for Bay beaches between Monroe County and the rest of the state may be that Bay beaches in Monroe County are well flushed due to the large expanse of Florida Bay and farther distance from the Florida peninsula directly behind the Keys. Thus bays in the Monroe County are more highly flushed compared to bays in the rest of the State resulting in better water quality (Corbett et al., 2000; Chanton et al., 2003).

Beach management was also associated with water quality. Higher exceedances were associated with the presence of homeless populations and policies that were less likely to be enforced with respect to animals. Beaches that do not charge fees typically had higher exceedances. Higher exceedances were typically associated with beaches that allow maintenance vehicles on the beach, have uncovered trash cans, and do not have a system in place for handling storm water. These results are consistent with those found in other studies including studies that focus on human (Elmir et al., 2009), dog (Wright et al., 2009), and bird

(Oshiro and Fujioka, 1995; Edge et al., 2010; Riedel et al., 2015) impacts, and studies that focus on the importance of revenue streams in long term maintenance (Kelly et al., 2018). Similarly, the influence of storm water management and proper waste disposal has been documented as important influences for environmental quality (Wright et al., 2011). Although all of these trends are consistent with suspected FIB sources, none of the differences were statistically significant. This may be due to the small sample size of beaches (n = 17) available through this focused study on Monroe County.

Increases in urbanization have been associated with increases in beach closures (Wu and Jackson, 2016), presumably due to greater amounts of FIB sources. A large potential contributor to regional FIB is sewage. In this study, regional improvements in sanitary infrastructure were associated with a decreasing trend in exceedances, thereby counteracting the effects of urbanization. Results from this study show an overall drop from 5.5% combined exceedance to 0.8%, indicating a reduction by a factor of about 7 in the exceedance rate after the infrastructure improvements. These encouraging results support the benefits of investments in the wastewater infrastructure. Similar findings were observed for a community on the opposite coast of Florida, which showed an overall significant reduction in the frequency of exceedances of fecal coliform and enterococci regulatory standards before and after remediation (Korajkic et al., 2011). Although the transition to more advanced wastewater treatment technologies has been slow due to limits in financial resources and communications (Sleasman, 2011), the progress appears to mirror improvements in beach water quality.

Results also showed that elevated temperatures in the 29 to 30 °C range were associated with maximum FIB levels. Assuming broadly that the FIB respond directly to temperature, then one can speculate about the potential influence of climate change on FIB levels. Recognizing that the mean temperature at the southernmost city in Monroe County, Key West, is 25.5 °C, global change can possibly contribute towards increasing FIB levels on average up through the mean temperature range of 29 °C. At this point, if temperatures continue to rise, FIB will likely decline as temperatures proceed above 29 °C. The possibility of increasing sea surface temperatures is considered to be part of anticipated climate change. Global sea surface temperatures are expected to rise by approximately 0.4 to 1.1 °C by the year 2025 (IPCC, 2013) with an increase up to 3.7 °C by the turn of the century. Our study therefore suggests that the mean temperature within the southernmost portion of the Florida Keys would reach the optimum for FIB survival by the year 2100. The increase to optimum temperature levels will also lengthen the period of time that bacteria can persist. With an increase in microbial persistence, the pathogenic microbes will also likely persist

longer, thereby increasing health outcomes associated with intestinal illnesses, eye and ear infections (Dvorak et al., 2018; Trtanj et al., 2016), especially among individuals who are at high risk (U.S. EPA, 2016). This will place an emphasis on beach management practices and infrastructure improvements to help lessen the burden we will undoubtedly expect.

Overall results were supported by the multivariate factor analysis which considered all of the measures evaluated in this study collectively. The results from the multivariate factor analysis suggests that, for the three years analyzed, parameters such as EDUs, air/water temperature, beach type, and the presence of homeless and concession stands seemed to remain significant throughout most of the period of study. While EDU and water temperature represent themselves as variables, variables such as the presence of homeless or concession stands may simply indicate a popular beach with a lot of human presence. Of interest is that the correlations with EDUs were positive suggesting that areas with higher EDUs (connections) were characterized by higher enterococci exceedances. This observation in terms of the spatial variation of the 17 beaches likely reflects the fact that more urban areas were prioritized for EDU connection services (e.g., Key West). When the enterococci data were evaluated temporally, a decrease in values were observed with increasing EDUs.

5. Conclusions

When viewed collectively, the results of this study suggest that several factors are associated with improved water quality. These factors include infrastructure upgrades, improved beach management, and greater beach water circulation as dictated by beach geomorphology. These factors can be adjusted to potentially offset reductions in water quality due to increased water temperatures from anticipated climate change.

This study also demonstrates the need to allocate resources to help facilitate beach managers in keeping beaches well maintained. The documentation of such improvements could only have been made possible through the long-term water quality monitoring efforts such as those through the Florida Healthy Beaches Program. Such monitoring efforts should continue into the future due to their value in assessing the effectiveness of infrastructure and beach management investments.

Although the analysis through this study suggests an association between temperature and FIB exceedances, further investigation is needed. The observed associations between FIB and temperature could have been due to secondary effects, such as the temperature at which people may utilize the beaches resulting in local releases of FIB that are not related to the survivorship of the bacteria at a given water temperature. To further establish the relationships with temperature, in situ studies are recommended to evaluate the survivorship of FIB under natural conditions under different temperatures.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2018.10.046.

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